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NRL Report 5441

BACKSCATTER AND DOPPLER FILTERS FOR THE PROJECT MUSIC RADAR

[Unclassified Title]

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ABSTRACT
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The storage, crosscorrelation radar developed under Project Music uses several types of passive filters which serve diverse purposes in the equipment chain preceding the data-analysis sections. Laboratory-developed filters were employed, as well as a commercially available type. Problems to which these filters were applied included, primarily, the elimination of interference by large-area signal return or backscatter, separation and limitation of the desired doppler frequencies, sideband elimination, and the removal of 60-cycle modulation from the received signal. The filter units incorporated into the Music system have given reliable service in the more than three years they have been in operation.

PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing on this and other phases.

AUTHORIZATION

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BACKSCATTER AND DOPPLER FILTERS FOR THE PROJECT MUSIC RADAR
(Unclassified Title)

INTRODUCTION

The Project Music radar system has as its ultimate goal the detection of low-flying aircraft targets, ballistic and guided missiles, and nuclear explosions, at ranges far exceeding normal line-of-sight distances.* This is to be accomplished by the use of ionospheric refraction in the hf band. The low frequency of operation of the Music system, namely 26.6 Mc, permits the transmitted energy to be refracted by the ionosphere downward toward the surface of the earth, where some of the incident energy will be reflected from a desired target back along the original path. However, a much larger portion of the energy will be scattered backward by the earth's surface also, to return via the same path. This latter signal, reflected from a very large area, known as backscatter, has been the downfall of previous attempts at utilizing the ionosphere for looking over the radar horizon for aircraft targets; the backscatter is enormous in amplitude compared to the desired echo, hence completely masking it out.

The flexibility incorporated into the Music radar allowed it to be used as a research tool. With this system, the backscatter phenomenon has been investigated, and the results have been reported previously.† In essence, it was found that the energy in the backscatter was contained within a ±4-cps maximum bandwidth around each spectral component of the radar signal. This suggested a means of eliminating the backscatter while preserving the desired echos. By sacrificing the first four cycles of the desired band of target doppler frequencies, the effects of the relatively enormous backscatter signals could be removed, previous to radar data processing, by using a narrow-band rejection filter centered on the second i-f frequency of 100 kc. Since it was unnecessary to preserve the echo pulse shape, a single rejection filter sufficed in place of a comb rejection filter. In designing the backscatter rejection filter, it obviously should be as narrow as allowed by the backscatter energy, so as to conserve as much as possible of the doppler signal band. Also, it must have sufficiently large attenuation in the rejection band to eliminate completely the backscatter, which can exceed the signal by more than 60 db.

Since only the doppler band about the carrier frequency was to be used, bandpass filters were designed to pass this band and exclude all of the other spectral signal and backscatter components. The design of the backscatter rejection filter, doppler-bandpass filters, and a 60-cps sideband rejection filter will be discussed. A simplified block diagram of the equipment is shown in Fig. 1, and a photograph of the Music system, less transmitter exciter, transmitter, and transmitter power supply, is shown in Fig. 2. It should be noted in Fig. 1 that a 100-kc mixer and two filter blocks are shown in the dotted outline. A detailed block diagram of this dotted portion is shown in Fig. 3.

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*A pioneer detection of evidence of a nuclear detonation was made by the Music radar system in August 1957. Detection of the launching of ballistic missiles was made in the 1957-1958 period; these studies are continuing.

†G. K. Jensen and C. L. Uniacke, "Spectral Bandwidth of Backscatter Signals," NRL Report 4976 (Unclassified), Aug. 1957.

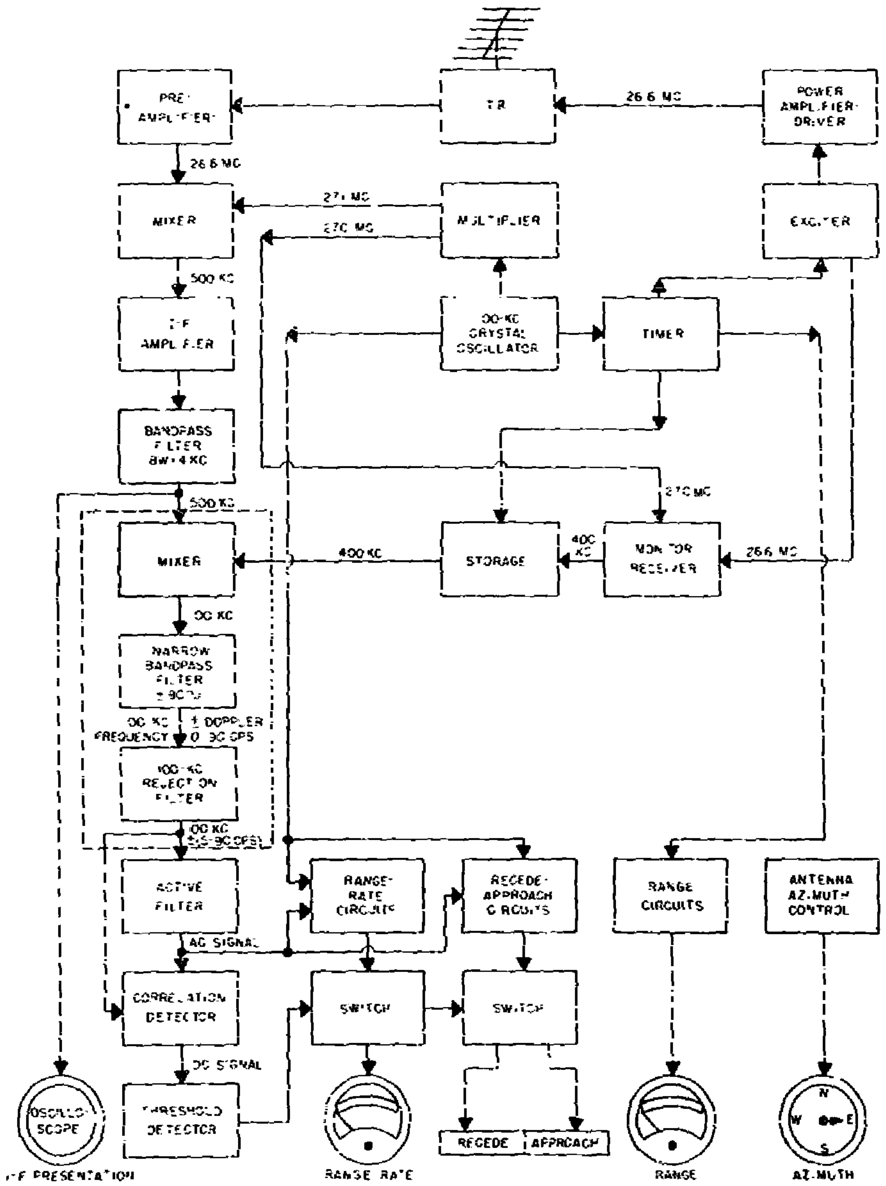


Fig. 1 - Music system, simplified block diagram. Note the circuits within the dashed line.

THEORY OF OPERATION

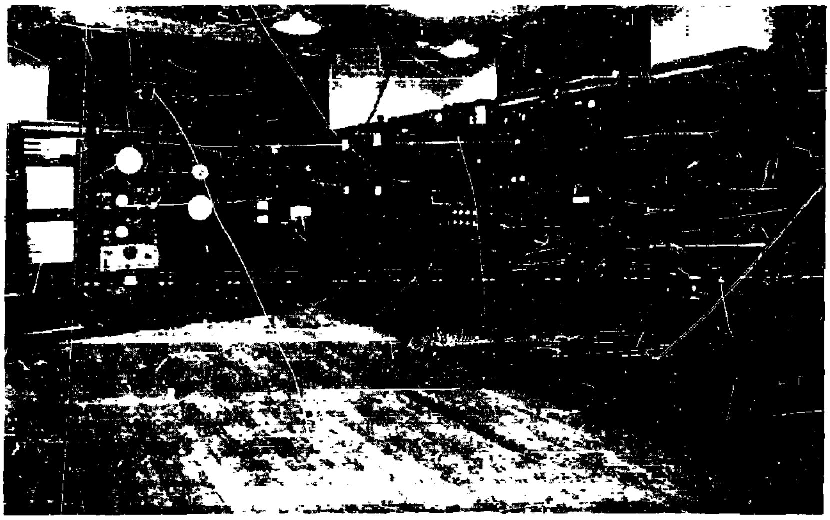
The Music radar system was developed in order to determine the practicability of employing correlation techniques for the detection of aircraft targets whose echo return was buried many decibels in noise. The ultimate aim, with sufficient transmitter power, is to detect aircraft targets beyond the horizon at ranges of about 1000 to 1500 miles. Many unanswered questions arose, such as the elimination of the backscatter return, which, at the operating frequency of 26.6 Mc, becomes a major deterrent to low-frequency radar. It was felt that the initial steps should be first to determine as much of the nature of the

Fig. 2 - Music system less transmitter

backscatter as possible, and second to make near-range detections (out to 160 nautical miles) in the presence of this backscatter an accomplished fact.

It was determined that the backscatter energy was contained in a bandwidth of plus or minus a maximum of four cycles around the backscatter spectral components. A sharp band-rejection filter was then employed to eliminate this bandwidth, thus sacrificing only the detection of 0 to 50 knot targets at an operating frequency of 26.6 Mc. Four information channels at a frequency of 100 kc plus and minus doppler frequencies were decided on as being sufficient to prove the principles of the system. Two of the channels are identical, except for the type of backscatter rejection filter used, and the third channel of the mixer, second converter further divides into a channel of 100 kc plus the doppler band and a second channel of 100 kc minus the doppler band (Fig. 3). This allows separation of returns into categories of approaching and receding targets. These doppler filters have been titled "dual band" for plus and minus doppler frequencies, and "upper" and "lower bands" for plus or minus doppler frequencies. The stop-band attenuation of these filters serves as an effective eliminator of unwanted sideband energy. It was necessary to place the bandpass filter ahead of the rejection filter to avoid reintroducing the backscatter signal contained in the sidebands into the final output due to slight nonlinearities in the circuits. These filters are followed in each of the four information channels by the narrow-notch backscatter rejection filters. The effectiveness of these filters is attested to by the fact that the backscatter return folded into the near range by the 500-cycle repetition rate was eliminated, allowing detection of aircraft targets out to 160 nautical miles with moderate transmitter power.

It was discovered during operational evaluations that a certain amount of 60-cycle frequency was being received and processed as target data. When detecting weak signals, occasionally a target with a velocity represented by the 60-cps line frequency was detected at all range intervals, being overridden only in the presence of strong local targets. Extreme precautions against hum modulation of the transmitter minimized the problem, but the extremely sensitive detection system still received a spurious 60-cycle doppler.



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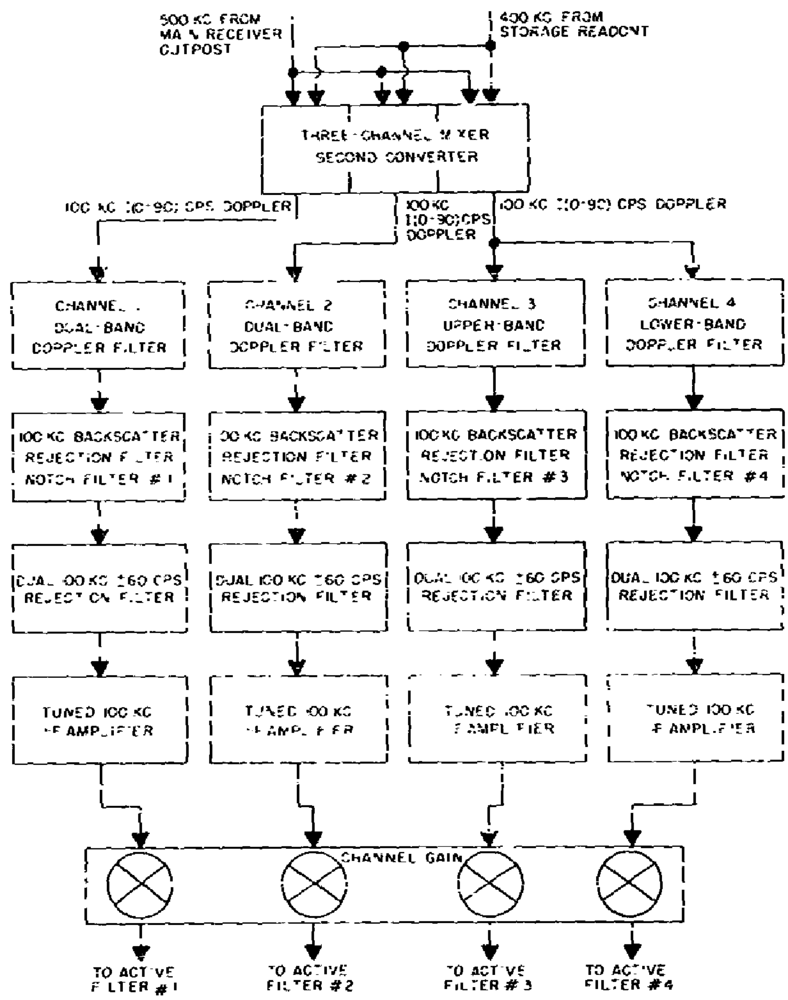

Fig. 3 - Second converter and filter channels, detailed block diagram. These circuits are those shown within the dashed line on Fig. 1.

This problem was completely eliminated by the insertion in each channel of a dual 60-cps notch, or rejection, filter which removed 100 kc ±60 cps.

Additional amplification in each channel of the 100-kc second i-f was added after the backscatter rejection filter, because receiver gain had to be kept low up to this point to avoid receiver overload on the high-level backscatter signal. The end result is a band of doppler frequencies with 60 cps, the backscatter bandwidth, and the sideband components removed, that is now available for target-data processing.

DESCRIPTION OF THE SYSTEM

The mixer, filter-chain units, and the 100-kc amplifier may be considered as the second conversion and second i-f of a double-conversion receiver. Two of the outputs from the three-channel mixer, second converter feed similar filter chains, while the third output splits to feed two additional filter chains. The first filter unit in channel one and channel two of the resulting four channels reduces the bandwidth around the 100-kc center frequency to a bandwidth necessary to accommodate the desired ±(0-60)-cps doppler frequencies. The channel-three and channel-four filters, of course, pass +(0-55) cps and -(0-55) cps, respectively. The next unit in each channel is a 100-kc rejection filter for backscatter bandwidth rejection, followed by a 100-kc ±60-cps rejection filter. And finally, in each channel is a tuned 100-kc i-f amplifier feeding a master gain panel.

The Three-Channel Mixer, Second Converter

The second conversion in the radar system utilizes the stored copy of the transmitted pulse, a signal burst of 400 kc, and the i-f signal from the main radar receiver containing the received echo information. This frequency of 500 kc is mixed in a 6AS6 vacuum tube with the 400 kc from storage, and the resulting output is 100 kc plus or minus the target doppler shift. The output will also contain the backscatter around each repetition-rate component. The output signal is coupled from the mixer plate circuit through a steep-skirted tertiary-coupled toroidal transformer with a bandwidth at 3 db of 10 kc centered on 100 kc. A cathode follower is incorporated to provide low-impedance output. A schematic diagram of this unit is shown in Fig. 4, and the linearity (or overload) characteristic is shown in Fig. 5. Channel one was chosen as being representative, since the unit consists of three identical channels.

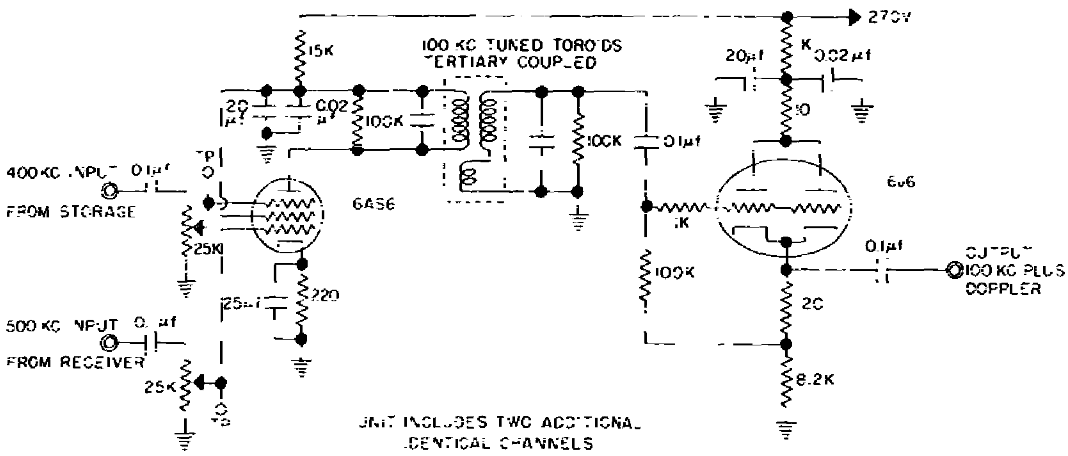

Fig. 4 - Three-channel mixer, second converter, schematic diagram

The Dual-Band Doppler Filter

The output of the second converter is 100 kc, plus or minus the doppler frequency range represented by the velocities of the targets of interest. It now becomes necessary to filter out frequencies beyond the nominally useful doppler range of ±60 to 80 cps centered on 100 kc. Consequently, for the two channels processing either approaching or receding targets, an LC bandpass filter was designed with a total 3-db bandwidth of approximately 140 cps centered on 100 kc. A schematic diagram of this unit is shown in Fig. 6. Inductances of high Q (approximately 450) were made possible by the use of ferrite cores and

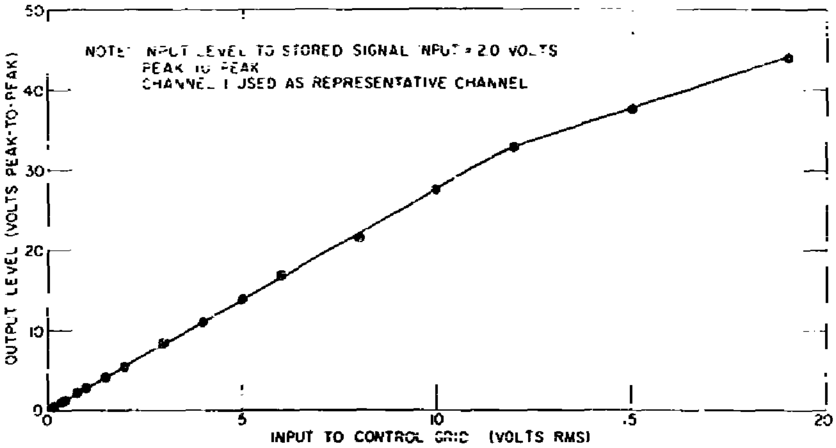

Fig. 5 - Three-channel second converter, linearity characteristic

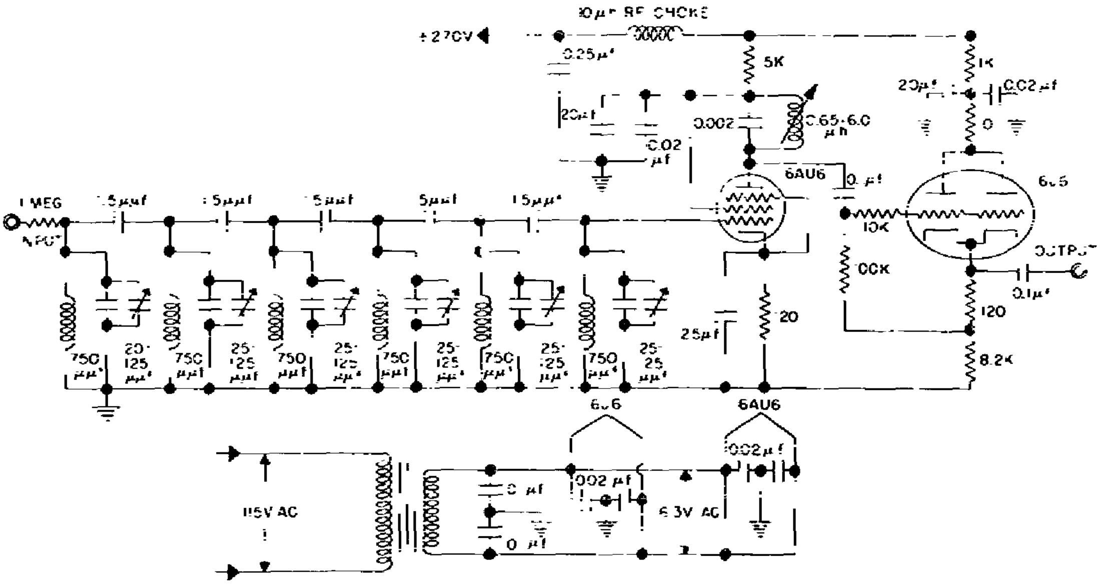

Fig. 6 - Dual-band doppler filter, schematic diagram

ferrite coil pots. The bandpass filter, then, consists of six high-Q tuned circuits mutually coupled by capacitive coupling, adjusted for a single peaked response rather than an over-coupled response, and each tuned element slightly stagger tuned to provide a degree of flat topping of the overall frequency response (Fig. 7). Insertion loss in the filter is much more than compensated by the gain in a tuned amplifier stage, which then drives a cathode follower for low-impedance output. The overall linearity characteristic for the dual-band doppler filter is shown in Fig. 8.

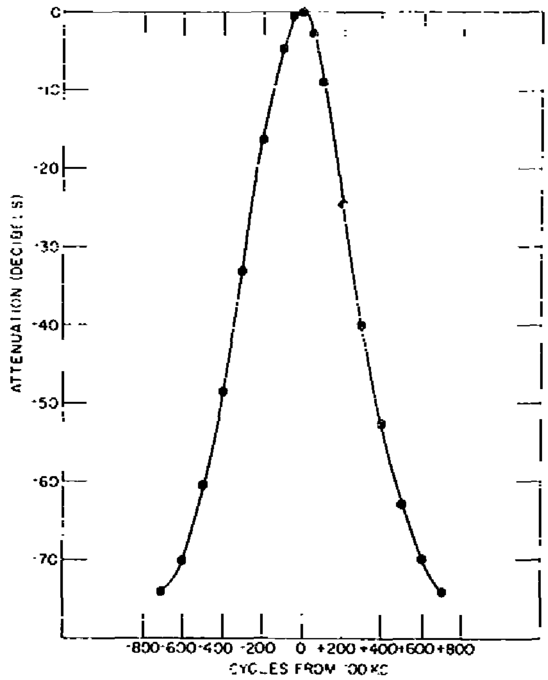

Fig. 7 - Dual-band doppler filter, frequency response

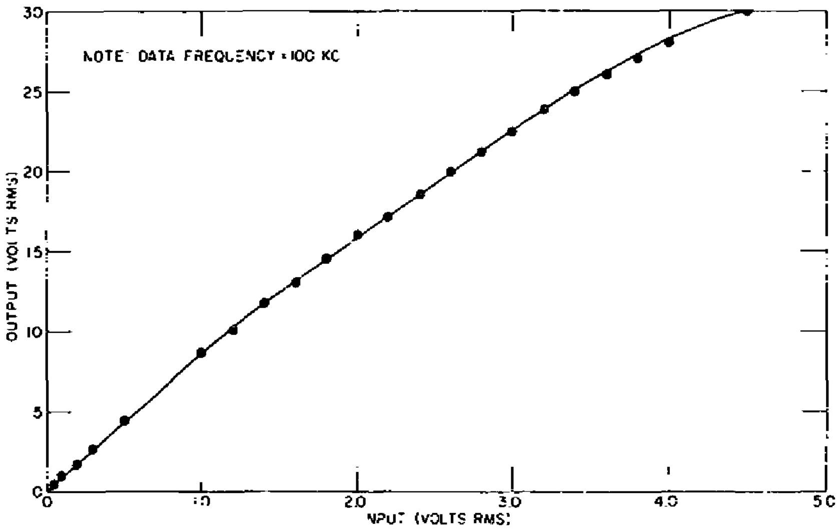

Fig. 8 - Dual-band doppler filter, linearity characteristic

The Upper-Band Doppler Filter

The upper-band doppler filter, as its name implies, allows only frequencies in the desired doppler band which occur above 100 kc to pass. The schematic diagram of this unit is shown in Fig. 9. Note that it takes the configuration of two sections of half lattice in cascade, each section driven by a phase inverter. The crystals used were selected for

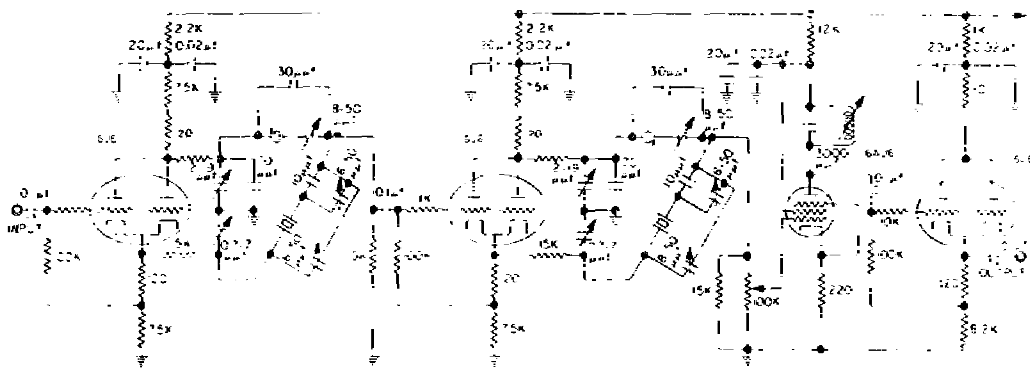

Fig. 9 - Upper-band doppler filter, schematic diagram

Q factors in excess of 100,000 and were tuned to the desired frequency by series capacitors in each crystal arm, as shown. The crystal frequencies employed were 100 kc +5 cps for the series arm and 100 kc -15 cps for the shunt arm, and, as may be seen from Fig. 9, each crystal is equipped with a series trimmer for series-resonance adjustment and a shunt trimmer for parallel-resonance adjustment. The crystals available were not ideally located in the frequency spectrum for the pass band desired, but they were capable of being pulled in frequency so that the parallel-resonant frequency of the lower-frequency crystal approximately equalled the series-resonant frequency of the higher-frequency crystal. It is possible to adjust the filter for high rejection near the pass band, thus producing steep skirts, but in this case, high attenuation was desired relatively far from the pass-band center frequency (±500 cps), and a low shape factor was not necessary. The response resulting from the filter described is shown in Fig. 10, and its linearity characteristic is in Fig. 11.

One of the design objectives was to use as few crystal-lattice sections as possible, yet fulfilling all the specifications placed on the filter, particularly for high attenuation beyond ±300 cps from the i-f frequency. As will be noted from Fig. 10, high attenuation was achieved with only two half-lattice sections. Very careful layout to prevent signals feeding directly from input to output helped achieve this result. Filter insertion loss was about 4.0 db. Additional gain in excess of this loss is provided by a tuned-amplifier stage which drives a cathode follower for low-impedance output.

The Lower-Band Doppler Filter

The lower-band doppler filter allows only those frequencies in the doppler band which occur below 100 kc to pass through for further processing. This filter unit is identical in its circuitry with the filter shown schematically in Fig. 9 and is identical in its operation. Note on Fig. 12 that the 3-db bandwidth points from the peak of the curve are approximately 100 kc -10 cps and 100 kc -55 cps. The filter is capable of still further attenuation in the stop band, but noise in the measuring setup was a limiting factor.

The Stagger-Tuned 100-kc Notch Filter

The removal by filtering of the backscatter frequency spectrum was an absolute necessity for detection of aircraft targets in the presence of high-level backscatter signals.

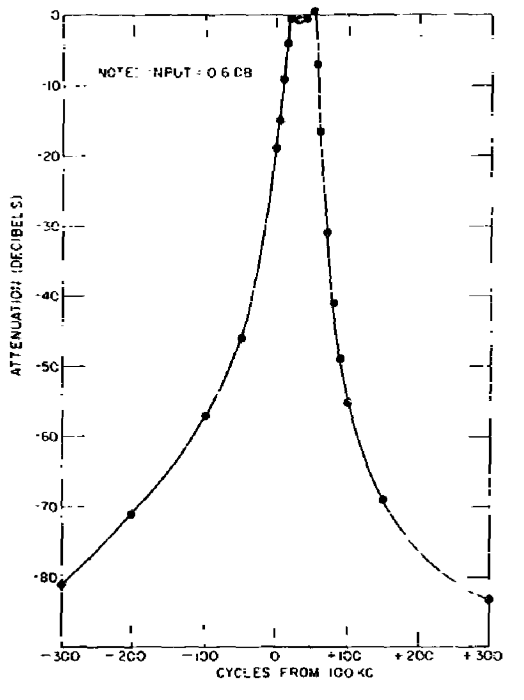

Fig. 10 - Upper-band doppler filter, frequency response

The knowledge of the frequency spectrum gained by previous studies* allowed the design specifications for a notch filter to be formulated. It was decided to purchase 100-kc narrow-notch filters from the Hycon-Eastern Corporation for use in the system. In the interim period, however, a notch filter was designed for incorporation into channel one. A rejection-filter design was initiated not only to reduce the time when a filter would be available but also to provide a narrower 3-db bandwidth, a wider bandwidth at the bottom of the stop band, and a larger attenuation in the stop band. This filter is shown in the schematic diagram in Fig. 13. As may be seen, it consists of four low-pass, cascaded filter sections with 100-kc crystals across the shunt capacitors. The crystals are series resonant, with the resonant frequency movable by means of series trimmers in the crystal legs. At frequencies off resonance, the crystal is an additional capacitance in parallel with a fixed shunt capacitor, which makes each section a constant-K type low-pass filter.

The cutoff frequency of this filter section is adjusted to be above the highest frequency passed in the channel. At frequencies approaching crystal resonance, the shunt-arm impedance drops sharply, inserting a narrow stop band in the low-pass filter response. The width of the notch is primarily determined by the Q of the crystal (series R), and in the case of the filter under discussion, the Q of the crystals used was in excess of 100,000. The first two sections were set for valley frequencies of 100 kc +1.5 cps and 100 kc -1.5 cps, respectively. The last two sections were then independently set for valley frequencies of 100 kc +3 cps and 100 kc -3 cps, respectively. The sections were then connected in cascade, and the high-frequency corner of the response was peaked to as sharp a break as possible, without excessive overshoot, by means of the shunt trimmers and inductances L1 and L2, shown in Fig. 13. The low corner was peaked with L3 and L4. The resulting frequency response is shown in Fig. 14. The filter sections drive a cathode follower for low-impedance output.

*Ibid.

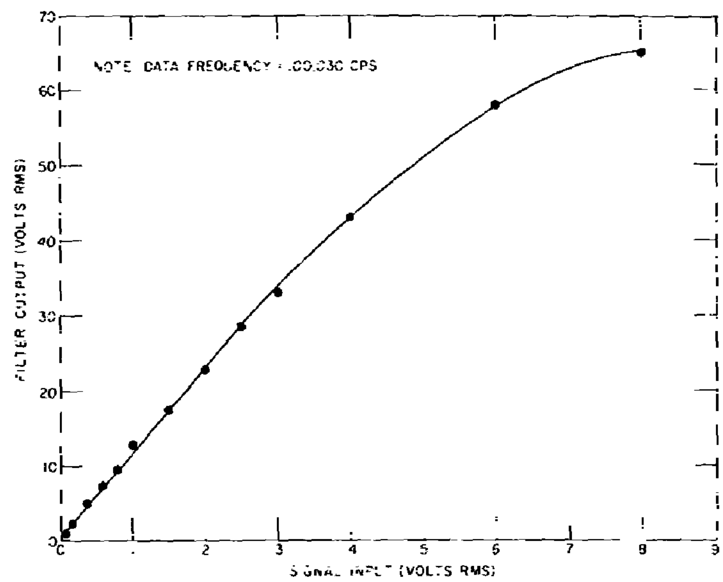

Fig. 11 - Upper-band doppler filter, linearity characteristic

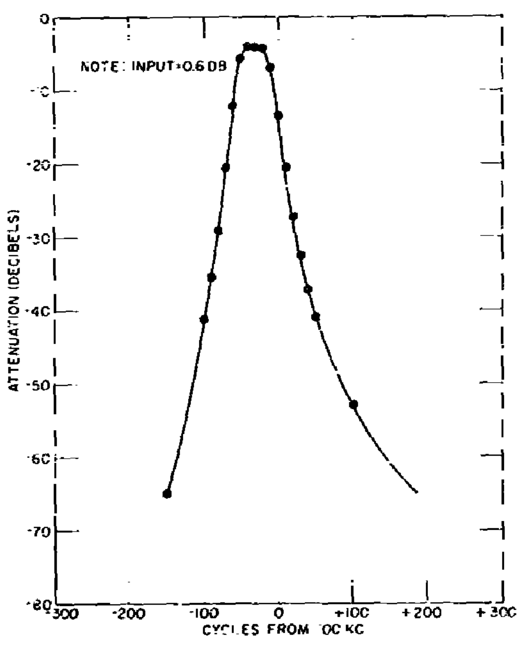

Fig. 12 - Lower-band doppler filter, frequency response

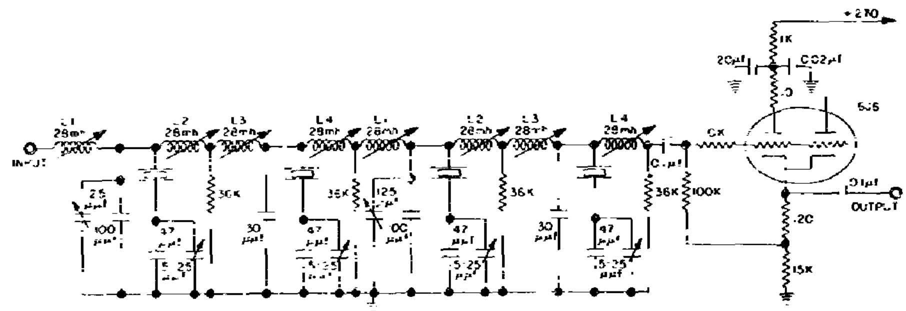

Fig. 13- Stagger-tuned 100-kc notch filter, schematic diagram

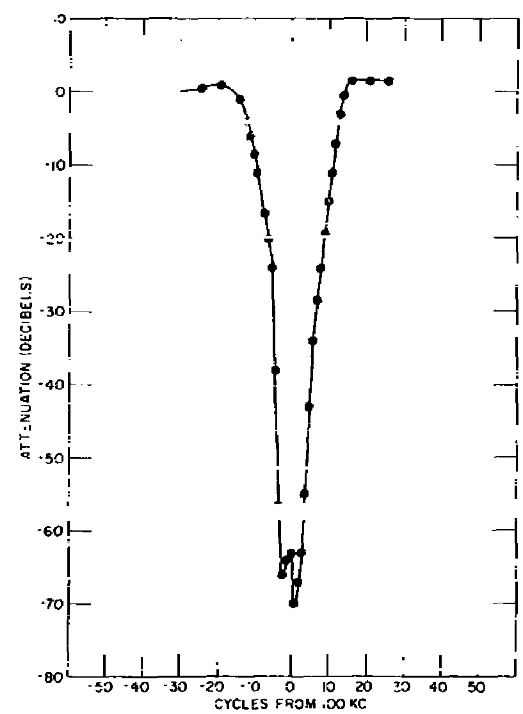

Fig. 14 - Stagger-tuned 100-kc notch filter, frequency response

The Hycon Eastern, Inc. 100-kc Notch Filter

The commercially produced 100-kc notch filters were checked, following their receipt, for adherence to specifications and installed in channels three and four. The filters were wider than was desired by about ±13 cps at the ±3-db points below zero attenuation. The Hycon filter, consisting of four filter sections in cascade, uses miniature crystals. A frequency-response curve for the Hycon-Eastern 100-kc notch filter is shown in Fig. 15. Since this filter was 26 cps wide at the 3-db points, it was decided to redesign it to reduce this bandwidth, to increase the attenuation in the stop band, and to reduce the number of sections, if possible. Figure 16 shows a schematic diagram of two sections of the filter redesigned for use in channel two.

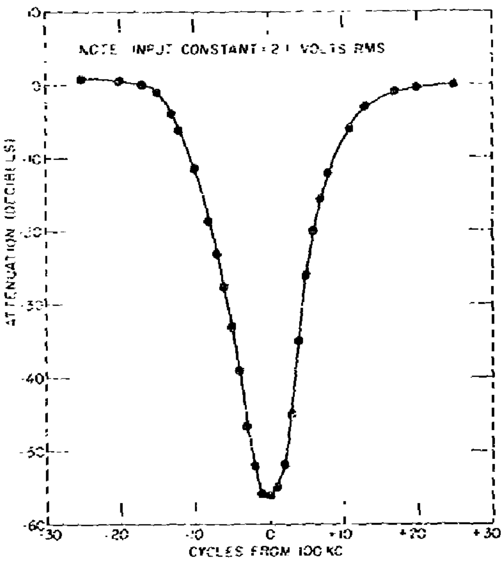

Fig. 15 - Hycon-Eastern, Inc., notch filter, frequency response

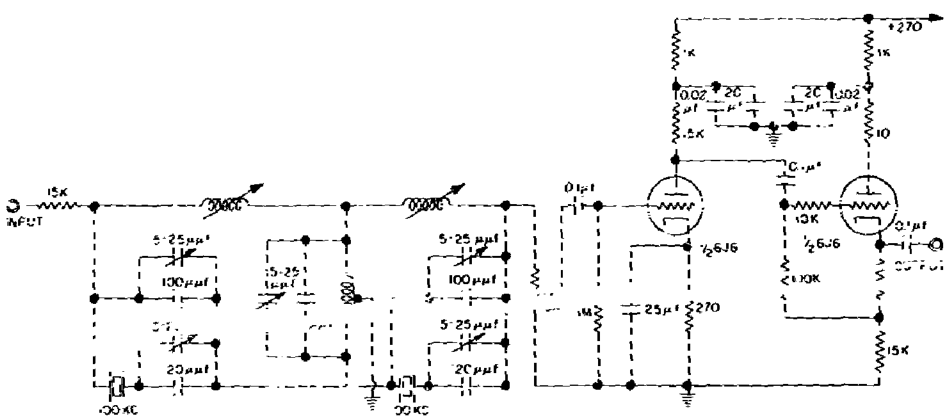

Fig. 16 - Redesigned Hycon-Eastern, Inc. 100-kc notch filter, schematic diagram

The Narrow 100-kc Notch Filter

By placing no size limitation on the unit, by physically isolating input and output, and by using high-Q crystals, the frequency response shown in Fig. 17 was obtained. A notch attenuation of 75 db and a 3-db bandwidth of approximately 10 cps were obtained. This filter has an amplification stage to overcome insertion loss and to provide overall gain, and a cathode follower for low output impedance.

The Dual 60-cps Notch Filter

A transmitter hum modulation, though slight, was nevertheless present at the filter channels as a spurious target with a 60-cps doppler frequency. This represented an

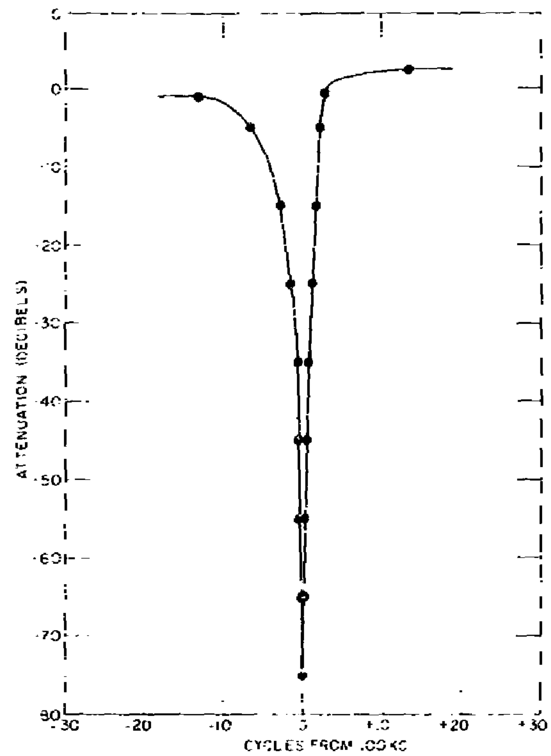

Fig. 17 - NRL 100-kc notch filter, frequency response

undesirable confusion in target determination, since it appeared as a relatively strong target in the data-processing units. This signal was reduced to a value below minimum detectable signal levels through the use of a crystal filter which attenuated frequencies of 100 kc +60 cps and 100 kc -60 cps. This unit is referred to as the dual 60-cps notch filter. A schematic of this unit is shown in Fig. 18. It is identical in operation with the 100-kc stagger-tuned notch filter shown in Fig. 13, except that it consists of only two low-pass filter sections and two crystals, one for 100 kc +60 cps and one for 100 kc -60 cps. Inductive tuning is provided for placing the 100 kc -60 cps notch exactly on frequency, and capacitive tuning for 100 kc +60 cps. The frequency response and linearity characteristics of this unit are shown in Figs. 19 and 20, respectively. Each of the four filter chains embodies a unit of this type and each, to all intents, is identical with the others of its type. Insertion loss is overcome and gain provided by an amplifier stage, and a cathode follower is incorporated for low-impedance output.

The Four-Channel 100-kc I-F Amplifier

The final unit, one of which is included in each filter chain, is a four-channel 100-kc tuned amplifier (Fig. 21). This unit, which may be considered to be the second i-f of the radar receiver, consists of a tuned amplifier of approximately 8-kc bandwidth followed by a cathode follower as a low-impedance output driver. The purpose of this four-channel unit is to provide gain more than sufficient for versatility of control. The output of each channel then feeds a master-channel gain-control unit which has final control for signals sent on to the data-processing equipment.

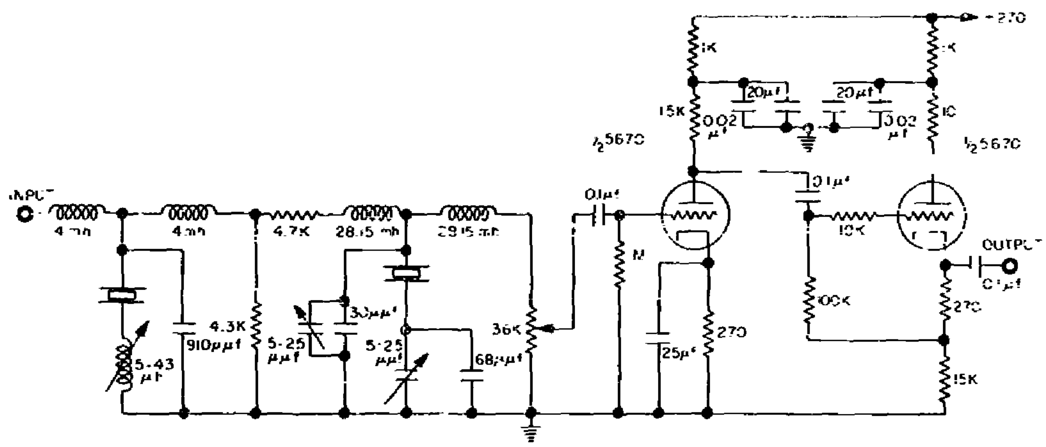

Fig. 18 - Dual 60-cps notch filter, schematic diagram

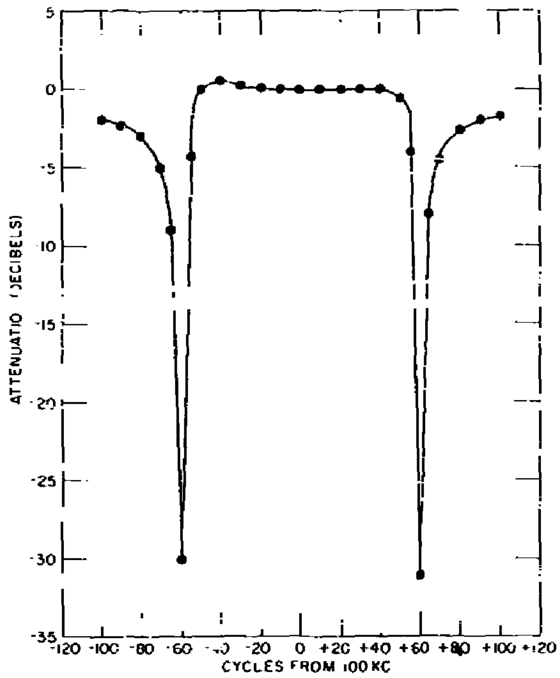

Fig. 19 - Dual 60-cps notch filter, frequency response

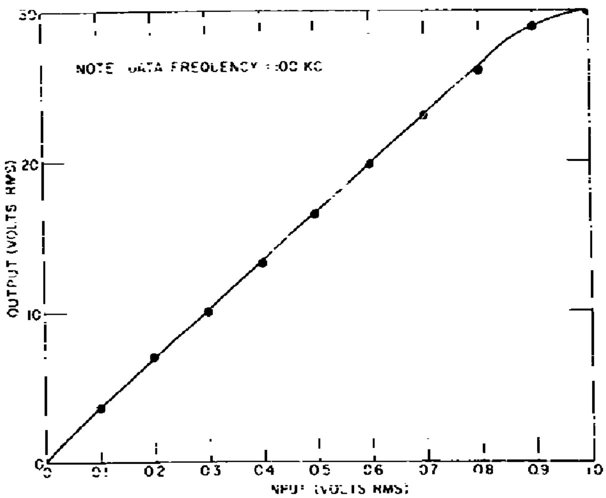

Fig. 20 - Dual 60-cps notch filter,
linearity characteristic

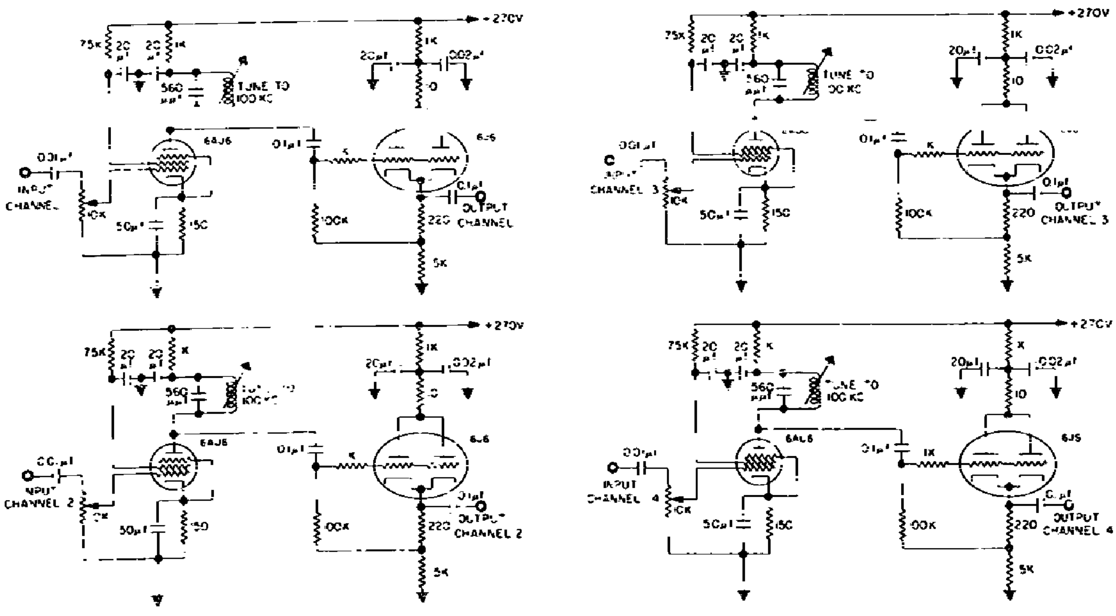

Fig. 21 - Four-channel 100-kc i-f amplifier,
schematic diagram

CONCLUSIONS

The Project Music radar system, because of its low operating frequency of 26.6 Mc, is capable of receiving ground return via ionospheric refraction from great distances. The basic repetition rate of 500 cps and base range of 162 nautical miles mean, however, that this large-area return (or backscatter) appears folded back in range and obscures all but the largest of local targets. A means of eliminating this backscatter had to be found, then, if detection were to be a possibility in the near range, to approximately 160 nautical miles, or, with higher transmitter power, in the far range to 1500 nautical miles. Studies made with the Music equipment on the nature of spectral bandwidth of backscatter indicated a possibility of filtering out about the second i-f of 100 kc a bandwidth of approximately ±4 cps, which should eliminate the backscatter signal. Filters were designed to overcome the problem of high attenuation and narrow bandwidth in the stop band. In addition to those designed, additional units were obtained commercially to the specifications submitted. This notching out of the backscatter of course meant sacrificing the very low doppler frequencies, which were deemed unnecessary in any case. The filters have been completely satisfactory, and many aircraft targets have been detected at ranges out to 160 nautical miles.

Narrow-bandpass filters were designed in order to limit the pass frequencies to those which occurred only in the doppler range of 100 kc ±(0-60) cps. These doppler pass filters also remove unwanted sidebands and lower the noise by bandwidth narrowing. Several types of pass filters were incorporated, including upper and lower doppler pass, upper doppler pass, and lower doppler pass. The filters, including both LC and crystal types, have been exceptionally reliable and effective since their installation.

Two spurious doppler frequencies that were unwanted were those occurring at 100 kc ±60 cps. These spurious targets were traced to the transmitter which, although carefully shielded and filtered, still put out a very-low-level 60-cps modulation component which was received and processed as the strongest target available. Consequently, a dual crystal rejection filter was designed to eliminate the 100-kc ±60-cps doppler frequencies.

In review, a three-channel mixer and four filter chains have been provided to feed four sections of data processing. Each filter chain has bandwidth-narrowed the signal to the doppler band around 100 kc, the backscatter bandwidth around 100 kc has been removed, and the ±60-cps doppler frequencies have been removed. Gain has been added to each channel by a four-channel 100-kc tuned i-f amplifier, and all mixer, filter, and amplifier units have performed the functions for which they were designed in a satisfactory manner.

ACKNOWLEDGMENTS

The authors acknowledge and commend the efforts of Mr. James H. Veeder for his valued work on the units herein described. To him goes the satisfaction of putting design into practice and watching the practice bear fruit.

* * *

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memorandum

5300-31

DATE: 29 June 1998

REPLY TO ATTN OF: Code 5300

SUBJECT: REQUEST TO DECLASSIFY NRL REPORTS

TO: Code 1221.1 (C. Rogers)

1. It is requested that the NRL Reports listed below be declassified. The information contained in these reports has become public knowledge in the many years since first classified.

Declassified, public release.

3706 AD-C954460	4371 AD-038472	[redacted]	[redacted]	5338 AD-312117	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	5399 AD-314113	5540 AD-320263
[redacted]	[redacted]	5126 AD/62728	5247 AD-304847	5403 AD-312699	5570 AD-320955
[redacted]	[redacted]	[redacted]	[redacted]	5441 AD-315354	
4284 AD031076	4878 AD-125352	5197 AD302457	[redacted]	5536 AD-343165	

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Mary Templeman

G.V. Trunk

G.V. TRUNK
Superintendent
Radar Division

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